Assessment of extreme flood events in changing climate for a long-term planning of socio-economic infrastructure in the Russian Arctic

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Abstract. Climate warming has been more acute in the Arctic than at lower latitudes and this tendency is expected to continue. This generates major challenges for economic activity in the region. Among other issues is the long-term planning and development of socio-economic infrastructure (dams, bridges, roads, etc.), which requires climate-based forecasts of the frequency and magnitude of detrimental flood events. To estimate the cost of the infrastructure and operational risk in affected regime, a probabilistic form of the long-term forecasting is preferable. In this study, a probabilistic model allowing to simulate the parameters of the probability density function (PDF) of multi-year runoff based on a projected climatology is applied to evaluate changes in extreme values of the flood depth of runoff for the territory of the Russian Arctic. The model is validated by cross-comparison of the modeled and empirical PDFs using the observations on 23 sites located in the northern Russia. The mean values and coefficients of variation (CV) of the flood depth of runoff are evaluated under 4 climate scenarios using simulations of six climate models for the period of 2010–2039. Regions with expected substantial changes in the means and CVs of the flood depth of runoff are outlined. For the sites located within such regions it is suggested to account for the future climate change in the evaluation of maximal discharges of rare occurancy. The example of engineering calculations of the maximal discharge with 1 % exceedence probability is provided for the Nadym River at Nadym City.

1. Introduction

The economic importance of the Arctic is increasingly recognized. Various governmental and commercial projects have been initiated internationally to develop the socio-economic infrastructure in the Arctic. Among others, there are projects for the oil and gas fields in Mackenzie Valley, Canada (Mackenzie, 2017), Prudhoe Bay, USA (Petrowiki, 2017), as well as the Pechora and Yamal regions, Russia (Gazprom, 2017). To design hydraulic constructions, such as dams, bridges, roads and pipelines, and to estimate the costs and risks of floods' damaging during the infrastructure's lifetime, an information is needed about the threshold values of dangerous river discharges. These values are calculated from the upper-tail of PDFs of the maximal river runoff. The PDFs are usually constructed with three parametric distributions (e.g. Pearson type III or Log Pearson type III) using the mean value, the coefficient of variation and coefficient of skewness (SP33–101–2003, 2004; Bulletin 17–B, 1988). These

parameters are calculated from observations with an assumption of stationarity of climate and hydrological regime (Thomas, 1985). It means that the values of the PDFs' parameters do not change in the future or during the period of operation of building constructions.

A great number of weather anomalies and detrimental flooding events are observed during the last decade. The changes in climate are especially expressed in the polar regions. Climate models project a robust increase in precipitation over the Arctic and sub-Arctic (Collins et al., 2013; Laine et al., 2014). During October through March, the precipitation amount in the Arctic is expected to increase by 35 % and 60 %, under medium and high greenhouse gas concentration pathways, respectively (RCP4.5 and 8.5), relative to the period 1986–2005 (IPCC, 2013). The projected precipitation increases in April through September are 15 % and 30 %, respectively. Due to climate warming and increased rainfall, annual-mean snowfall is projected to decrease over northern Europe and mid-latitude Asia, but to increase in northern Siberia, especially in winter (Krasting et al., 2013). Further, precipitation extremes are projected to increase, the climate model results being robust particularly for northern Eurasia in winter (Kharin et al., 2013; Toreti et al., 2013; Sillman et al., 2013). In Siberia these increases in the precipitation will be accompanied by a decrease in the number of consecutive dry days (Sillman et al., 2013). Over northern Eurasia, the net precipitation (precipitation minus evapotranspiration) is also projected to increase during winter. The projected changes discussed above are likely with a high confidence (Collins et al., 2013), and therefore point to an urgent requirement to better evaluate the response of the other components of the Arctic freshwater system, including terrestrial hydrology (Prowse et al., 2015).

There are two opposite opinions about the climate change and their effects to hydrological regime to answer the question: "Is it necessary to account for climate changes by water managers and stakeholders?" According to Milly et al. (2008) the climate change effects are already substantial, and should be taken into account by planers and water managers. The opposing view doubts a climate-driven changes and calls to attention the uncertainties due to short observed time series (Lins and Cohn, 2011; Montanari and Koutsoyiannis 2014; Serinaldi and Kilsby, 2015). We propose to account for the future climate change on environmental risks even in case if the uncertainties can not be fully evaluated or are unknown. Ii is better to prevent accidents than to deal with their consequences, which may be more expensive than the initial investment. We consider that the changes in meteorological variables would remain noticed in runoff, which is an element of general water balance. From a practical point of view, methods to evaluate the extreme flood events are required irrespectively of debates about extent or reality of the climate change (Madsen et al., 2013).

For flood estimation two main approaches are usually applied. The deterministic approach is based on a combined use of a regional climate model (RCM) and a physically-based rainfall-runoff hydrological model (Fig. 1). RCMs provide the future meteorological forcing variables with a high temporal resolution to drive a hydrological model that describes complex physical processes, such as infiltration, snow melting, and evapotranspiration. This allows generation of synthetic time series of river runoff (discharges) for individual watersheds, and the flood events with required exceedance probability are then estimated from the simulated time series. Successful applications of this approach include numerous studies (Veijalainen et al., 2010; Lawrence et al., 2011; Archeimer and Lindström, 2015). The large scale rainfall-runoff models have also been used to assess the changes in the flood frequency by Lehner et al. (2006) for the European Arctic. The shortcoming of these studies is that the results are sensitive to the algorithms of the calculation of a pseudo-daily

precipitation input from projected climatology provided by Global Circulation Models (Verzano 2009). The second approach to evaluate the hydrological response to the expected climate change is stochastic. Weather generators are used to simulate time series of meteorological forcing for the physically-based hydrological model (Kuchment and Gelfan, 2011). Thus, estimates of the extreme hydrological events (floods or droughts) with the required exceedance probability are obtained for a climate scenario by producing the meteorological signal with Monte-Carlo method. Both approaches are usually applied for a single catchment. In regional scale analysis, the runoff should be simulated for a set of watersheds. It makes the calculations extremely costly computationally, especially in the case of climate ensembles.

The approach presented in this paper could be named as probabilistic (to distinguish from the stochastic modelling described above). This approach allows us to skip the generation of the runoff time series, since only PDF parameters are directly calculated from the meteorological statistics for the projected periods of 20–30 years (Fig. 1). These simulated PDF parameters are further used to evaluate the future runoff values with the required exceedance probability using theoretical distributions from the Pearson system (Elderton et al., 1969). Since the probabilistic model simulates only three-four parameters of PDF, this approach allows easy performing of a regional scale assessment of detrimental hydrological events in the future, and to define the regions where the risks of damage for infrastructure increase.

The probabilistic approach used in this study combines the statistical methods and elements of theory of Markov processes. Both of them are traditionally applied in the hydrological engineering calculations to evaluate design floods (Kite, 1977; Benson, 1968; Kritsky and Menkel, 1946). The traditional frequency analysis of flood and drought requires the hydrological time series to estimate the parameters of PDFs and to calculate the runoff of requred exceedance probability. However, the parameters of PDFs can be also estimated from the statistics of meteorological variables. The idea to perform the direct simulation of the PDFs' parameters from the climate projections (without the simulation of time series) is proposed by Kovalenko (1993). Kovalenko et al. (2010) simplified the basic probabilistic model for the engineering hydrology, and Viktorova and Gromova (2010) applied this approach to produce a regional scale assessment of the future drought extremes for the European part of Russia.

The main idea of the simplified method is the "quasi-stationarity" of the changing climate and hydrological regime for the periods of 20–30 years. This idea allows us to represent the multi-year runoff statistically with a set of PDFs' parameters for the particular time window; the set is different for the past (or reference period) and the future (or projected period) climatology. Thus, the climate change could be accounted for in the calculations of the runoff tailed values, which are usually required for the assessment of risks in water management. The IPCC recommends the climate projections, which are represented as the multi-year means of the meteorological values for the period of 20–30 years (Pachauri and Reisinger, 2007), i.e. under the same quasi-stationarity assumption.

The probabilistic model provides a more economical way to produce the hydrological projections for the extremes on a regional scale. This is because of (i) a low number of the forcing and simulated variables (only three-four statistics of climate and hydrological variables are needed); (ii) a low number of the parameters (physical processes are described integrally by a lumped hydrological model); and (iii) a relative simplicity of a regionally oriented parameterization.

Furthermore, the probabilistic model does not require the large spatially distributed datasets and may be applied for the regions of poor data coverage, such as the Arctic.

The aim of this study is to perform a regional scale assessment of the future extreme floods based on climate projections for the Russian Arctic. The novelty of the study includes two aspects. First, we present the method to assess the frequency and magnitude of extreme floods in changing climate, adapted in this case to the Arctic territories. It could also be applied to other territories, as the regionally oriented parameterization is relatively simple. Second, the paper provides the projected changes in the mean values and CVs of the flood depth of runoff under 4 climate scenarios for the Russian Arctic. The regional scale assessments are based on the Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathway (RCP) scenarios. The regions are delineated, where the frequency and magnitude of floods are expected to change substantially. Maps include a warning for the regions where an engineering calculations of the extreme maximal discharges should be corrected to account for the climate change. An example of the engineering calculation of maximal discharge of 1% exceedance probability for the Nadym River at Nadym City is provided using the outputs of three climate models for the period 2010–2039.

2. Methods and data

The idea of the method used in this study is to simulate the future parameters of PDF of the multi-year peak runoff using the projected mean values of precipitation and air temperature. Then, to construct the PDF with simulated parameters and a priory defined theoretical distribution (Pearson Type III), and finally to calculate the maximal runoff with required exceedance probability. This idea was used to perform the regional scale assessment of the maximal runoff for the northern territories of Russia, where the peaks occur during the spring. On these territories, the peak runoff is usually formed by seasonal snow melting and may be expressed as the spring flood depth of runoff (h, mm/(time period)), which is the volume of spring flood runoff (m^3) from a drainage basin divided by its area (m^2). The spring flood depth of runoff was chosen instead of the maximal discharge because this allows mapping of the spatial distribution of maximal runoff. Thus, the spring flood depth of runoff can be used in defining the regions for which the design maximal discharges should be corrected according to climate change. After such regions were delineated, the correction of the maximal discharge with required probability of exceedance can be done using climate projections.

From the spring flood depth of runoff, the river discharge with a required exceedance probability (Q_p, m^3s^{-1}) is calculated according the method proposed in SP33–101–2003 (2004):

$$Q_p = k_0 \mu h_p \delta \delta_1 \delta_2 F / (F+b)^n , (1)$$

where k_0 is the flood coincidence factor, which reflects a simultaneousness of precipitation/melting water input, i.e. depends on the shape of the hydrograph; μ is the factor of inequality of the depth of runoff and maximal discharge statistics; h_p is the spring flood depth of runoff (mm/(time period)) with probability p (0.1, 0.05, 0.01) estimated from the exceedance probability curve (or PDF); $\delta, \delta_1, \delta_2$ are the watershed fractions of lake, forest and swamp respectively; F is the watershed area (km^2); b is the additional area which adjusts the reduction of the runoff (km^2) and n is the degree of a runoff reduction. For the ungauged basin the value of k_0 is estimated from observations on a neighboring gauge located on a same type of landscape (SP33–101–2003, 2004). In our study, the value of k_0 was considered to be constant for the reference and projected periods. The values of $\mu, \delta, \delta_1, \delta_2$, b and n may be

obtained from look-up tables (SP33–101–2003, 2004) or from global datasets representing land cover (e.g. Bertholomee´ and Belward, 2005).

2.1 Model

The core of the probabilistic hydrological model is a linear differential equation with stochastic components having solutions statistically equivalent to solutions of the Fokker–Planck–Kolmogorov (FPK) equation (Pugachev et al., 1974). It allows the evaluation of the probability density function of a random hydrological variable with parameters dependent on climate variables. Under a quasi-stationary assumption of the climate change, the FPK is approximated by a system of algebraic equations to simulate initial statistical moments of multi-year runoff (Kovalenko, 1993, 2014) (see Annex for details). These moments are further used to calculate the PDFs' parameters and to model them using the theoretical formulations (e.g. Pearson Type III). In our study, the simple model suggested in Kovalenko et al. (2010) was used to model the statistical moments of the flood depth of runoff :

$$\begin{aligned} -\bar{c}\,m_1 + \bar{N} &= 0 \\ -2\,\bar{c}\,m_2 + 2\,\bar{N}\,m_1 + G_{\widetilde{N}} &= 0 \end{aligned} \quad , (2)$$

where m_1 (mm) and m_2 (mm^2) are the first and second initial statistical moments of the flood depth of runoff for the period of 20–30 years; $\bar{c}=1/k\tau$ is the inverse of the runoff coefficient k (which is a dimensionless coefficient, the ratio of the amount of runoff to the amount of precipitation received) times the watershed reaction delay τ ; $\bar{N}$ (mm) is the mean value of annual precipitation amount for a period of 20–30 years. The parameter $G_{\widetilde{N}}$ (mm^2) reflects the variance of annual precipitation.

The system of Eq. (2) allows evaluating the multi-year runoff statistical moments for the projected time period based on the climatology and multi-year runoff statistics for the reference (historical) period. The climate and runoff regime are steady within both the reference and projected periods (the assumption of quasi-stationarity). The "steady" is defined statistically, i.e. there are no significant trends and changes in mean values of the meteorological and hydrological characteristics within the periods. However, the basic statistics (mean, CV and CS values) are significantly different for the reference and projected periods.

The system of Eq. (2) was applied as follows:

  − (i) the initial statistical moments from the observed hydrological and meteorological time series for the chosen reference (r) period (m_{1r}, m_{2r} and $\bar{N}_r$) were estimated;

  − (ii) the model parameters for the reference period were assessed:

$$\bar{c}_r = \bar{N}_r / m_{1\text{r}} \,,$$

$$G_{\widetilde{N}\,r} = 2\left(\bar{c}_r\,m_{2\text{r}} - \bar{N}_r\,m_{1\text{r}}\right) \,, (3);$$

  − (iii) the future (f) values of 2 statistical moments ($m_{1\text{f}}$ and $m_{2\text{f}}$) from the projected mean of the annual precipitation $\left(\bar{N}_f\right)$ were calculated:

$$m_{1f} = \bar{N}_f / \bar{c}_f ,$$

$$m_{2f} = \left(2 \bar{N}_f m_{1f} + G_{\tilde{N}f} \right) / 2 \bar{c}_f , (4).$$

The values of the parameters $\bar{c}_f$ and $G_{\tilde{N}f}$ were set either constant for the projected time period (as proposed by Kovalenko et al. 2010)), or dependent on the future climatology. To evaluate the projected values of the parameter $\bar{c}$ depending on the average precipitation and air temperature, the linear equations are suggested by Shevnina (2012) were used. In our study, the parameter $G_{\tilde{N}}$ was considered to be constant for the projected time period.

− (iv) the future the mean value and CV were obtained. The future CS was calculated from the given ratio of CS/CV which was considered to be constant for the reference and future periods. The future PDFs were constructed (with Pearson type III theoretical distribution) and used to estimate the spring flood flow depth of runoff with the required exceedance probability. Then, the peak discharges were calculated using Eq. (1).

2.2 Validation

Rainfall-runoff models are usually validated against observed time series (Lehner et al., 2006; Arheimer and Lindström, 2015). The system of Eq. (2) allows simulating the parameters of PDF of the multi-year runoff without producing time series. The predicted parameters of the PDFs for the one time period are based on the parameters of PDFs calculated for the other period. Two time periods should have the different values of the parameters and the difference should be statistically significant (Kovalenko et al., 2010). Such kinds of periods were found in the observed time series to perform the probabilistic model validation using a cross-validation procedure. In the simplest cross-validation procedure, the observational dataset is separated into 2 sub-sets, called the training set and the testing/control set. From the training set the model parameters are evaluated and then used to predict nominally the parameters of the control PDFs (Kovalenko, 1993). In our case, the nominally predicted PDF was compared with the empirical distribution for the testing/control period using the Pearson chi-squared and Kolmogorov-Smirnov one-sample tests.

The whole period of observations was divided into the sub-periods with the statistically significant difference (shift) in the mean values. Dividing into the subsamples was done according to the Student's t-test using the moving window approach (Ducré-Robitaille et al., 2003). We begin from setting the size of the first subsample to the chosen minimum (15 members). The size of the second subsample in this case is the size of the total sample (N) minus the chosen minimum ([N-15] in Fig. 2). Between these 2 subsamples we calculate the value of t-test. Then, the size of the first subsample was incremented by the iterator i=1, 2, 3 … until the size of the second subsample became equal to the chosen minimum. The values of t-test were calculated for each step and were linked to the years of the time series subdivision. Finally, the whole time series was divided by the year with t-test exceeding the critical value of 0.05 level of statistical significance. The Student's test critical values accounting the asymmetry and autocorrelation in hydrological time series were used (Rogdestvenskiy and Saharyuk, 1981). If several partitioning years were found, we gave preference to the year that divided the time series into 2 approximately equal sub-periods.

The initial first and second statistical moments of the flood depth of runoff for each sub-period were calculated according to Bowman and Shenton (1998). The third moment was estimated from the entire time series, and the ratio of CS/CV was calculated. Then, the mean values of the annual precipitation and air temperature for each sub-period were also calculated. The resulting dataset included pairs of the statistical moments for the flood

5   depth of runoff (m_1^{I}, m_1^{II}, m_2^{I}, m_2^{II}), the mean values of air temperature $\left(\bar{T}^{I}, \bar{T}^{II}\right)$ and annual precipitation $\left(\bar{N}^{I}, \bar{N}^{II}\right)$.

For the cross-validation, we: (i) considered the first sub-period as the training and calculated the reference values of the model parameters; (ii) predicted nominally ("in the past") the first and second moments for the second sub-period (which was considered as control). The same procedure was applied backwards. We validated 2

10   versions of the model: (i) with the basic parameters setting as proposed by Kovalenko et al. (2010) and (ii) with the regional-oriented parameterization as suggested by Shevnina (2012). The empirical and nominally predicted PDFs were compared for each sub-period and the goodness-of-fit between them was estimated using the Pearson chi-squared and Kolmogorov-Smirnov one-sample tests. If the value of the test did not exceed the critical value of 0.05 level of statistical significance, nominally prediction of PDF was considered to be successful. The model

15   prediction scores were obtained as a percentage of the matching PDFs for the whole dataset.

The model cross-validation was performed with observations collected during the period from 1930s to 2000s. The observed data were extracted from the official edition of the Multi-Years/Year Books of the State Water Cadastre of the Russian Federation (see e.g. Kuznetsov, 1966). The spring flood depth of runoff time series at 76 gauges for medium size catchments (1,000–50,000 km^2) were used. The gauges are located on the territory of the

20   Russian Arctic. The gauging sites are irregularly distributed over the territory with 65 % of the points located at the west part of the Arctic. The time series lengths vary from 26 to 77 years with an average of 51 years. The dataset has no gaps in the time series of 66 % of the considered gauges. The time series for 18 % of the gauges have the missing values for more than 5 % of their length.

The example of the cross-validation for the Yana River at Verkhoyansk gauge is shown in Fig. 2. For the

25   partition of time series into 2 sub-periods, the time series (Fig. 2, top) was first divided at the point S=1949 and the *t*-test value was calculated. Then the *t*-test values were calculated step-by-step until the point E=1987 with increments of 1 year. At the point A=1965 (Fig. 2, bottom), the *t*-test exceeds the critical value at 0.05 level of statistical significance. Thus, 2 periods were differentiated: the first sub-period, covering the interval 1935–1964 with m_1^{I}=41.2 (mm) and the second sub-period covering the interval 1965–2002 with m_1^{II}=52.3 (mm). The

30   second statistical moments (m_2^{I}, m_2^{II}) of each period were calculated as well. Then, the average values of the annual precipitation amount $\left(\bar{N}^{I}, \bar{N}^{II}\right)$ and the annual mean air temperature $\left(\bar{T}^{I}, \bar{T}^{II}\right)$ were also calculated for the two sub-periods. The reference values of the parameters $\left(\bar{c}_r, G_{\widetilde{N}r}\right)$ were estimated using $m_1{}^{\mathrm{I}}{}_{\mathrm{r}}$, $m_2{}^{\mathrm{I}}{}_{\mathrm{r}}$ and $\bar{N}_r^{I}$ for the sub-period 1935–1964 (considered as training). Then, the nominally predicted or modeled $m_1{}^{\mathrm{II}}{}_{\mathrm{f}}$, $m_2{}^{\mathrm{II}}{}_{\mathrm{f}}$ were calculated from $\bar{N}_f^{II}$ for the sub-period 1965–2002 (considered as control). Finally, the nominally

35   predicted mean value and CV were calculated from the simulated runoff statistics and CS was estimated from the

ratio of CS/CV for each period. These values were used to nominally predict PDF (or the exceedance probability curve – Fig. 3) with the Pearson type III distribution. Then, the nominally predicted and empirical PDF were compared (Fig. 3). The same procedure was done backwards: the sub-period 1965–2002 was considered as training and the statistical moments were nominally predicted for the sub-period 1935–1964 (considered as control in this case).

The sub-periods with statistically significant shift in the mean values of the flood depth of runoff were selected for 23 time series (Table 1), which is 30 % of the considered data. For the corresponding watersheds, the average values of the annual precipitation amount and the mean air temperature were calculated using the observations from 37 meteorological stations (approximately 2 stations per watershed) for each sub-period (Table 1). The observed meteorological time series were obtained from Razuvaev et al. (1993), Radionov and Fetterer (2003), Bryazgin (2008, personal communication) and the multi-year catalogs of climatology (e.g. Catalogue, 1989).

For each gauge and sub-period, the statistical moments were nominally predicted using Eq. (4) for the 2 versions of the model parameters settings (Table 2). We also compared these predictions with the case, when the nominally predicted PDF for one sub-period was modeled using the statistical values calculated from the observed data of the other sub-period ("no model" case). The "no model" case illustrates the "stationary climate" scenario in which climate change is not taken into account, and thus the PDFs' parameters are not modified for the period of prediction. This case reflects the situation as considered in the guidelines for the engineering hydrology (SP33-101-2003, 2004; Bulletin 17–B, 1982), when only observed runoff time series to evaluate the PDF parameters were used. The percentage of the nominally predicted PDFs that matched successful to the empirical PDFs according to Pearson chi-squared and Kolmogorov-Smirnov one-sample tests were evaluated for each version of the model parameterzation. Table 3 provides the percentage of the successful coincidences of the PDFs, which was obtained from the available cross-validation dataset (46 pairs of the simulation and empirical PDFs).

The model with the constant parameters gives a more conforming result than the case of "no model": the percentage of successfully matched PDFs is over 5–10 percentage points higher. Using the regional parameterization algorithm to calculate the parameter $\bar{c}$ gives the even more reliable result, with the values 11–22 percentage points higher. Hereinafter, we used the regional-oriented parameterization scheme to estimate the future PDFs' parameters of the flood depth of runoff based on the climate change projections.

2.3 Data and method application

In performing of the long-term assessment of the extreme flood events in the Russian Arctic the reference period was chosen from 1930 to 1980, the projected period was from 2010 to 2039. The following datasets were used: (i) the climatology for the reference period (Fig. 4 a, b), (ii) the mean values and CV of the spring flood depth of runoff for the reference period (Fig. 4 c, d), and (iii) the climatology for the projected period (Fig. 4 e, f). The reference climatology was obtained from the catalogs of climatology and the archive of the Arctic and Antarctic Research Institute for 209 meteorological stations (Radionov and Fetterer, 2003; Catalogue, 1989). The climatology was interpolated into the model grid nodes using the algorithm by Hofierka et al. (2002). For the precipitation we use the annual values although the spring floods are formed only by a snowfall and spring

rainfall. However, in the Arctic the relationship between spring flood depth of runoff and both annual and winter-spring sums of precipitation are strong (Shevnina, 2011).

The climatology for the projected period is provided by the climate models (Pachauri and Reisinger, 2007; Taylor et al., 2012). In this study, the projections of 2 Emissions Scenarios (SRES: A1B and B1) and 2 Representative Concentration Pathways (RCPs: 2.6 and 4.5) scenarios were extracted from CMIP3 and CMIP5 datasets. Results of climate models of Max Planck Institute for Meteorology MPIM:ECHAM5 (Roeckner et al., 2003), the Max Planck Institute Earth System Model MPI–ESM (Giorgetta et al., 2013), the Hadley Center for Climate Prediction and Research HadCM3 (Johns et al., 2003), HadGEM2–A (Collins et al., 2008), the Geophysical Fluid Dynamics Laboratory GFDL:CM2 (Delworth et al., 2006) and by the Canadian Center for Climate Modelling Earth System Model CanESM2 (von Salzen et al., 2013) were used. These GCMs produce approximately similar climate projections. This allows to show that the hydrological modelling results do not vary much under the slightly different climate forcing. To obtain the climate forcing, the projected mean values of air temperature and precipitation were corrected using the delta changes method (Fowler et al., 2007). For that, the relative changes of the variables (in degrees for the temperature and in % for the precipitation) were first calculated based on the historical simulations and observed climatology for the reference period. Then these changes were added/multiplied to the projected climatology. The corrected mean values of the annual precipitation and annual average air temperature were estimated for the nodes of corresponding climate model grids.

The means and CVs of the spring flood depth of runoff were extracted from the maps Rogdestvenskiy and Vodogretskiy (1986) in the following way by scanning of the paper maps, image georeference, digitizing of data and interpolation to the grid nodes of the particular GCM. These maps were designed based on the observations for the period since early 1930s till 1980 (Rogdestvenskiy, 1988). In producing these maps the observations on the catchments of medium size (from 1,000 to 50,000 km^2) located within the single climate zone were used. Thus, the features of runoff processes on the local scale (appeared on small watersheds) and global scale (revealed on huge watersheds located within several climate zones) as well as floods due to ice jams and tides/surges were not considered. In our study no time series of multi-year runoff were used to evaluate the mean value and CV for the reference period and no extrapolation was applied for the regions without observations.

The values of $\bar{c}$ and $G_{\widetilde{N}}$ were calculated using Eq. (3) for each node of the particular climate model grid. Then, the future first and the second initial statistical moments were calculated according to Eq. (4) using the projected climatology, and future values of CV of the spring flood depth of runoff were evaluated. The future values of CS were estimated using the regional ration of CS/CV in assumption that it is constant for the reference and projected period. The maximum discharge with the required exceedance probability was calculated according to Eq. (1) (see Section 3 for the example). Our study was performed for the period 2010–2039, since within this interval the existing and developing socio-economic infrastructure (bridges, oil/gas pipelines, roads and dams) will operate.

3. Result and discussion

The analysis of the expected climate change in Russia and particularly over the Arctic is provided by Govorkova et al. (2008) and Meleshko et al. (2008). These studies consider the territories of the Russian Federation as a whole. In our study we provide the estimates within the geographical domain of the Russian Arctic, which was outlined according to the hydrological principles as suggested by Ivanov and Yankina (1991) and further used by Nikanorov et al. (2007). The projected climatology averaged over the Russian Arctic is presented in Table 4 for the SRES and RCP scenarios. Generally, an increase of annual precipitation over 20 mm (6 %) and warming of over 2.1 °C were predicted according to the SRES scenarios. For the RCP scenarios, the changes were more pronounced, with the precipitation mean values expected to increase by more than 40 mm (12 %), accompanied by a warming of 3.3 °C. The strongest increase (over 60 mm or 16 %) in precipitation with the highest warming (over 3.9 °C) was predicted by CaESM2 for the RCP 2.6 scenario (Table 5).

The future means and CVs of the spring flood depth of runoff were assessed from the projected climatology using the method described above. For the entire territory of the Russian Arctic an increase of over 27 mm (17 %) in the mean values and a slight decrease of CVs were predicted according to the SRES scenarios (Table 4). Using scenarios of the Fifth Assessment Report, the changes in the statistics of the spring flood depth of runoff were more notable: based on the RCP 2.6 scenario, an increase of over 38 mm (23 %) in the mean values and a decrease of over 0.03 (16 %) in the CV's were expected. The strongest increase (over 45 mm or 27 %) of the means with a lowest decrease of the CVs (over 0.06 or 17 %) was predicted by CaESM2 for the RCP 2.6 scenario.

According to all scenarios considered, the highest increase of the future means of the spring flood depth of runoff (of 30–35 %) was predicted for Arkhangelsk Oblast and the Komi Republic (Fig. 5b). Moderate changes in the mean values (of 10–18 %) are also predicted for Siberia (Fig. 5c and 5d) mostly according to the RCP scenarios. For the SRES scenarios, an increase of 10–18 % in the mean values was predicted for the Kola Peninsula and Karelia (Fig. 5a), accompanied by a decrease of CVs.

We can not to compare our results with other studies directly because we address different flooding characteristics. Only indirect comparison is possible. For the comparison, we assume that for the Pearson type III distribution, an increase in the means and CVs leads to an increase of upper-tail values. Subsequently, present 100-year floods will occur more frequently (Fig. 6). Also, a decrease in the means and CVs leads to a decrease in the upper-tail values. In this case, we can expect that the number of events of 100-year floods decreases. We compared our results with the studies by Hirabayashi et al. (2008; 2013), Lehner et al. (2006) and Dankers and Feyen (2008) using this assumption. For the eastern part of the Arctic, an increase in the historical 100-year maximum discharges is predicted by Hirabayashi et al. (2008; 2013) under the SRES:A1B scenario for the period 2001–2030. This is in accordance with our results; we also expect an increase in the upper-tail runoff values since the mean values and CVs were estimated to increase in general for this region. For the north-east European Arctic we expect a significant increase in the frequency of present 100-year flood events. This is in contrast to Hirabayashi et al. (2013). The flood frequency decreases in many regions of northern and eastern Europe according to Hirabayashi et al. (2013). The feasible reason for such disagreement is that the model used by Hirabayashi et al. (2013) is very coarse: it was calibrated using observations from watersheds larger than

100,000 km^2. In our study, the probabilistic model was calibrated using observations for watersheds of medium range. Lehner et al. (2006) used the WaterGAP model with climate projections derived from the HadCM3 and ECHAM4/OPYC3 GCMs. The results suggest that present 100-year flood events will occur more frequently in the north-eastern European Arctic in 2020s, which is in accordance with our results.

5   For the Kola Peninsula and Karelia, we predicted a decrease of the mean values with slight increase of the CVs according to the SRES:A1B and SRES:B1 scenarios. Dankers and Feyen (2008) suggested a strong decrease of present 100-year floods for north-eastern Europe (i.e. Finland, northern Russia and part of the Baltic States) under the SRES:A2 and SRES:B2 scenarios, which is generalby in agreement with our results. A similar tendency of maximal discharges to decrease was predicted for the northern Finland (Veijalainen et al., 2010).

10   There are several sources of uncertainties in the method described above: (1) from the assumed (given a priori) type of distribution (Pearson type III); (2) from the limited length of hydrological time series, which were used to evaluate the parameters of the distribution for the reference period; (3) from the limited length of meteorological time series to evaluate the climatology for the model parameterization; (4) from the uncertainties in future climatology provided by climate models (forcing); (5) from the mapping errors due to interpolation techniques; (6) from the errors due to the

15   calculation of the maximal discharges from the spring flood depth of runoff (Eq. (1)). The uncertainties inherent to the simulated PDF parameters include items 1–5 from the list above. These uncertainties are evaluated by Kovalenko (1993) for the maps of means/CVs, provided by Pogdestvenskiy (1986) and Vodogretskiy (1986) in assumption that the errors in the future and past climatology are the same. The average percentage errors in the projected means/CVs are equals to 15 % / 25 %, thus it is suggested to consider the changes in the PDFs' parameters to be substantial if they

20   exceed the reference values for more than these thresholds. The regions with substantial changes in the means and CVs of the spring flood flow depth are shown in Fig. 7.

In these regions the frequency and magnitude of floods were predicted to differ substantially from the historical (reference) period. The changes in the mean values and coefficients of variation were predicted according to the outputs of the climate models of the Max Planck Institute for Meteorology: MPIM:ECHAM5 for the SRES:B1

25   scenario and MPI-ESM-LR for the RCP 2.6 scenario. A substantial increase in the mean values is expected for Arkhangelsk Oblast, Komi Republic and Eastern Siberia (see Fig. 8 for the boundary of the regions). These are warning regions where the flood related risks for hydraulic constructions in the future may be different from the past. In these regions, the calculations of the maximal discharges should be corrected in line with the expected climate change.

30   The example of the climate-based correction for the Nadym River at Nadym City according to climate model outputs for the RCP 2.6 scenario is given below. A new bridge over the Nadym River was constructed in 2015 and repaired afther the spring flood in 2016. The maximal discharge of rare occurrence (e.g. 1% exceedance probability) is required to assess the bridge height and cost. The watershed of the Nadym River is located in the region, where the increase of the mean spring flood depth of runoff was predicted under RCP2.6 scenario (Fig. 7, right, upper plot). Thus, the

35   climate change impacted upper-tail maximal discharge may be well larger than the value estimated from the observed time series. Hydrological observations for the Nadym River are available at Nadym City (gauge number 11805, the watershed area is 48,000 km^2, see the bottom panel of Fig. 8). The statistics of the spring flood depth of runoff for this gauge were calculated from the observations for the period of 1954–1980, which was considered as reference in this

case (Table 6). The reference climatology was calculated by averaging the observations from the regular meteorological sites for the Nadym River catchment area for the same period. Then, the projected climatology with delta correction for the period of 2010–2039 under the RCP 2.6 scenario was obtained from the CMIP5 dataset. The parameter $G_{\widetilde{N}}$ was estimated according to the observed climatology and the parameter $\bar{c}$ was calculated from the projected climatology according to Shevnina (2012). These values were used to predict the first and second initial statistical moments, and coefficient of variation (m_1, m_2 and CV) of the spring flood depth of runoff. The projected CS was estimated from the given ratio of CS/CV. The projected PDF was obtained from these values together with the spring flood depth of runoff 1 % exceedance probability ($h_{1\%}$, mm) (Table 6). The confidence intervals for the reference values of $h_{1\%}$ were calculated using the formulas suggested by Ashkar and Bobée (1988) in assumption that the given distribution is Pearson type III. The 90% confidence interval for the reference $h_{1\%}$ equal to ±64.5 mm, which is about 23 % of the quantile value. The projected values of $h_{1\%}$ are within these uncertainties for all considering climate scenarios (Table 6), thus due to the short time series we can not prove that the future changes in $h_{1\%}$ are statistically insignificant. However, we suggest to take into account for the projected climatology in calculation of hydrological risks because of practical reasons: it is better to prevent an accident rather than to deal with its consequences, which may be more expensive than the initial investment (Räisänen and Palmer, 2001). Finally, the maximal discharge with 1 % exceedance probability ($Q_{1\%}$, m³s⁻¹) was estimated from $h_{1\%}$ according to Eq. (1). The values of the parameters of Eq. (1) were taken from the look-up tables (Guideline, 1984). The value of k_0 was considered to be constant for the reference and projected periods and set to be equal to 1 in our example for sake of simplicity; μ equals to 1.0; δ, δ_1, δ_2 equal to 0.84, 0.06 and 0.08 correspondingly; b equals to 1.0 (km²) and n equals to 0.17.

For the period of 2010–2039 the maximal discharge of 1% exceedance probability, calculated with averaging of the multi-model output, is 570 m³s⁻¹ larger than the discharge of the same probability of exceedance calculated from the observations. The largest increase of the maximal discharge was predicted according to the CanESM2 model (over 7% larger than the historical value). The maximal discharge of 8572 m³s⁻¹ changed the probability of exceedance from 1% (calculated from the observations) to 2.5 % (calculated according to the averaged climate projections).

4. Conclusions

A probabilistic approach was applied in estimating the impact of the climate changes to the frequency and magnitude of extreme floods in the Russian Arctic. The probabilistic hydrological model predicts the future runoff extremes with the required exceedance probability directly, without simulation the future runoff time series. The projected meteorological mean values for the periods of 20–30 years were used to estimate the future means, CVs and CSs of the spring flood depth of runoff, and to model the PDFs with a Pearson type III distribution. The future frequency and magnitude of extreme floods with a required exceedance probability were then evaluated from the simulated PDFs.

In this study, to perform the model cross-validation, the runoff data were extracted from the official issues of Roshydromet, however, in calculating multi-year time series of spring flood depth of runoff (and maximal discharge), the global and regional runoff databases may be also used. The examples of the datasets are (i) the Global Runoff Data Centre, Germany; (ii) the Environmental Information System (HERTTA), Finnish Environment Institute; the Vattenwebb by the Swedish Meteorological and Hydrological Institute. To perform the assessments for the other regions, steps are following: (i) to choose the middle size watersheds with catchment area from 1,000 to 50,000 km^2; (ii) to calculate the multi-year time series of runoff (yearly maximal discharges or flood depth of runoff) from the daily runoff time series; (iii) to select the time period without statistically significant trends (reference period); (iv) to estimate the mean values, CVs and CSs from the observed time series of runoff or to evaluate them from the regional maps (i.e. Spence and Burke, 2008) and the statistics of the precipitation and air temperature; (v) to perform the model parameterization using general (Kovalenko et al., 2010) or the regional-oriented schemes (Shevnina, 2012); (vi) to assess the mean values of the precipitation and air temperature from the results of the GCM/RCM models for the future; and (vii) to evaluate the future means, CVs and CSs of multi-year runoff with Eq. (4). To perform the model cross-validation and to develop the regional-oriented parameterization scheme, the multi-year time series of runoff with the periods of statistically significant shifts in the mean values and CVs are required.

The probabilistic model was further applied for a regional scale assessment of extreme flood events for the Russian Arctic. The regional-oriented parameterization by Shevnina (2012) allows a successful prediction of 67–83 % of the PDFs (see Section 2.2). The projected mean values, CVs and CSs of the spring flood depth of runoff for the period 2010–2039 were estimated under the SRES:A1B, SRES:B1, RCP 2.6 and RCP 4.5 climate scenarios with outputs of three climate models. For the region studied, an increase of 17–23 % in the mean values of spring flood depth of runoff and a decrease of 5–16 % in the CVs were predicted depending on the scenarios considered. For the northwest of the Russian Arctic, an increase in the means and a decrease of the CVs were predicted. The regions with substantial changes in the mean values (over 15 %) and CV (over 25 %) were defined for 2010–2039. For the territories where the means and CVs increased substantially, the extreme floods are predicted to occur more frequently and the risk of flooding is increased. We suggest to correct the hydrological engineering calculations, and account for the projected climatology. It might reduce the risk of a potential hazard for the hydraulic constructions, the oil-gas industry, the transport infrastructure and population located in these warning regions.

The model presented in this study provides an affordable method to produce forecasts of extreme flood events (in the form of PDF or as maximal discharge with a required exceedance probability) under the projected climate change. This is possible due to low number of the simulated variables and parameters. The regionally-oriented parameterization of the model is also relatively simple and may be improved by involving a variance of precipitation, which could be obtained from the projected climatology (Meehl et al., 2011). However, due to various simplifications, the model presented in this study does not allow an estimation of possible changes in spring flood timing or changes of intra-seasonal runoff variability for a particular watershed. On a regional scale, however, the method provides an explicit advantage to estimate extreme hydrological events under altered climate, especially for regions with an insufficient observational data. It could be useful for a broad-scale

assessment to define the warning regions, where crucial increase/decrease of the extreme flood events is expected. When the warning regions are defined, a catchment scale rainfall-runoff model could be applied to further distinguish details not anticipated by the method described in this study. Such models also allow to evaluate the value of the spring flood coincidence factor k_0 (Eq. (1)) for the projected periods (which was constant in our calculations). The evaluation and inter-comparison of the presented model and rainfall-runoff models is of high interest.

Another weak point of the method is the use of look-up tables for physiographic parameters. In our study, to calculate the extreme discharges of the Nadym River we used look-up tables for the territory of the former Soviet Union from Guideline (1984). For other regions world-wide, these physiographic parameters may be derived from spatially distributed datasets, e.g. according to Bertholomee and Belward (2005). Also, an issue to be studied is the effect of the spatial resolution of projected climatology on the ability of the this model to estimate the frequency/magnitude of extreme floods for watersheds of different size.

The method described in this study was simplified for the use of engineering calculations, as the projected climatology for the periods of 20–30 years recommended by IPCC (Pachauri and Reisinger, 2007) assumes a quasi-stationary climate. In general, the quasi-stationarity assumption may be eliminated and a non-stationary regime could be considered. In this case, the PDFs could be evaluated based on the full form of the Fokker–Planck–Kolmogorov equation (Domínguez and Rivera, 2010) with the multi-model climate ensemble approach (Tebaldi and Knutti, 2007).

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Data availability. Our study is based on third party data. The citations to the data sets have been included in the reference list.

Competing interests. The authors declare that they have no conflict of interest.

Annex.

The concept of the probabilistic modeling to obtain a hydrological response to an expected climate change was proposed by Kovalenko (1993), it is presented further as provided in Kovalenko et al. (2010). This approach considers multi-year runoff time series (annual, maximal and minimal) as realizations of a discrete stochastic Markov chain type process (Rogdestvenskiy, 1988). Then, a first order ordinary differential equation is used as a lump hydrological model for the multi-year flow time series:

$$dQ/dt = -\left(1/k\tau\right)Q + \dot{X}/\tau \text{ , (A1)}$$

where Q is some runoff characteristic depending on a task (the discharge, the volume per year, the runoff depth per year, *etc.* – "model output"); $\dot{X}$ is the precipitation amount per year ("model input"); k is the runoff coefficient; τ is the time of reaction of the watershed to the incoming precipitation (here, τ =1 year, which physically means that the precipitation amount during one year generates the runoff from the watershed during one year); t is the time interval, equals to one year. Denoting $c=1/k\tau$ and $N=\dot{X}/\tau$ and adding random components ($\tilde{c}$, $\widetilde{N}$ stand for "white noise") to $c=\bar{c}+\tilde{c}$ and $N=\bar{N}+\widetilde{N}$ we obtain the stochastic differential equation:

$$dQ=\left[-(\bar{c}+\tilde{c})Q+(\bar{N}+\widetilde{N})\right]dt \text{ . (A2)}$$

The random components are mutually correlated.

The solution of Eq. (A2) is statistically equivalent to the solution of the Fokker-Planck-Kolmogorov equation (Pugachev et al., 1974):

$$\frac{\partial p(Q;t)}{\partial t}=-\frac{\partial}{\partial Q}(A(Q;t)p(Q;t))+0.5\frac{\partial^2}{\partial Q^2}(B(Q;t)p(Q;t)) \text{ , (A3)}$$

where $p(Q;t)$ is the probability density function of the multi-year runoff characteristic (Q is considered now as a random value); $A(Q;t)$ and $B(Q;t)$ are the drifting and diffusion coefficients:

$$A(Q;t)=-(\bar{c}+0.5G_{\tilde{c}})Q-0.5G_{\tilde{c}\widetilde{N}}+\bar{N} \text{ ;}$$

$$B(Q;t)=G_{\tilde{c}}Q^2-2G_{\tilde{c}\widetilde{N}}+G_{\widetilde{N}} \text{ , (A4)}$$

here, $G_{\tilde{c}}$ and $G_{\widetilde{N}}$ are the measures of variability of c and N; $G_{\tilde{c}\widetilde{N}}$ is the measure of correlation between the variability of $G_{\tilde{c}}$ and $G_{\widetilde{N}}$.

In engineering hydrological applications and flood frequency analysis only three-parametric probability density functions are used (Bulletin 17–B, 1988). Then Eq. (A3) may be simplified to a system of ordinary differential equations for three statistical moments m_i (i = 1, 2, 3):

$$dm_1/dt=-(\bar{c}-0.5G_{\tilde{c}})m_1-0.5G_{\tilde{c}\widetilde{N}}+\bar{N} ;$$
$$dm_2/dt=-2(\bar{c}-G_{\tilde{c}})m_2+2\bar{N}m_1-3G_{\tilde{c}\widetilde{N}}m_1+G_{\widetilde{N}}; \qquad \text{(A5)}$$
$$dm_3/dt=-3(\bar{c}-1.5G_{\tilde{c}})m_3+3\bar{N}m_2-7.5G_{\tilde{c}\widetilde{N}}m_2+3G_{\widetilde{N}}m_1.$$

This system can be used to calculate the statistics of the multi-year runoff: the mean $\bar{Q}=m_1$, the coefficient of variation $CV=\sqrt{(m_2-m_1^2)}/m_1$ and the coefficient of skewness $CS=(m_3-3m_2m_1+2m_1^3)/(C_v^3m_1^3)$.

Additionally, the constant value of CS/CV ratio for the projected time period was used to simplify Eq. (A5). This assumption is commonly applied in engineering hydrological applications to estimate the regional CS. Also, the climate scenarios are distributed by IPCC as mean values of meteorological variables for the periods of 20–30 years. Thus, scenarios for the expected for climate change are presented with an assumption of "quasi-stationarity" and this may also be applied for the hydrological regime. This allows further simplifications of Eq. (A5):

$dm_i/dt\approx 0$ and $G_{\tilde{c}},G_{\tilde{c}\widetilde{N}}=0$ within these periods. Hence, Eq. (A5) may be reduced to only 2 algebraic

equations for m_1 and m_2:

$$-\bar{c}\,m_1 + \bar{N} = 0$$
$$-2\bar{c}\,m_2 + 2\bar{N}\,m_1 + G_{\widetilde{N}} = 0$$

This system may be applied to estimate the multi-year hydrological statistical moments directly from climatology for each "quasi-stationary" time period.

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Table 1. Sub-periods with the statistically significant shift in the mean values of the spring flood depth of runoff with the multi-year statistics and climatology.

Notations: m_1 and m_2 are the initial first and second statistical moments of the spring flood depth of runoff; CV is the coefficient of variation; CS is the coefficient of skewness; $\bar{N}$ is the annual precipitation amount; $\bar{T}$ is the annual air temperature.

Gauge ID	River	Catch-ment area [km²]	Period	m_1 [mm]	m_2 [mm²]	CV	CS/CV	$\bar{N}$ [mm]	$\bar{T}$ [°C]
01176	Bohapcha	13600	1934–1949	111	15401	0.50	2.5	421	−12.1
			1950–1980	141	23907	0.45	2.8	435	−12.4
01309	Seimchan	2920	1941–1956	190	40779	0.36	3.1	373	−11.5
			1957–1977	157	25842	0.22	5.1	305	−11.4
01623	Srednekan	1730	1935–1950	148	25067	0.38	4.0	426	−10.7
			1951–1980	180	36145	0.34	4.5	431	−11.1
03403	Malaya Kuonapka	2030	1943–1985	97.5	10848	0.36	0.8	255	−13.8
			1986–2002	116	14297	0.25	1.1	262	−13.1
03414	Yana	45300	1935–1964	41.1	2190	0.55	1.2	177	−14.8
			1965–2002	52.1	3456	0.48	1.4	178	−14.6
03518	Nera	2230	1944–1985	67.0	5439	0.46	0.8	227	−15.8
			1986–2002	84.6	8214	0.37	1.0	222	−14.4
09425	Turukhan	10100	1941–1970	232	56198	0.21	1.3	491	−7.4
			1971–1999	260	70304	0.20	1.4	494	−7.4
11574	Pyakupur	31400	1954–1970	142	21140	0.22	4.2	482	−6.4
			1971–2001	162	27884	0.23	3.7	514	−6.0
11805	Nadym	48000	1955–1974	162	27632	0.23	3.0	490	−6.4
			1975–1991	140	21607	0.32	2.2	471	−5.0
70047	Solza	1190	1928–1958	190	38356	0.25	0.9	525	1.3
			1959–1980	155	26046	0.29	0.8	552	1.0
70153	Yug	15200	1931–1946	126	16716	0.23	2.0	575	1.6
			1947–1980	144	22994	0.33	1.4	591	1.6
70180	Vychegda	26500	1930–1956	147	22960	0.25	0.0	491	−0.1
			1957–1980	167	29632	0.25	0.0	550	−0.5
70360	Lodma	1400	1939–1958	219	53184	0.33	1.2	533	0.7
			1959–1977	174	32650	0.28	1.4	546	0.7
70366	Kuloy	3040	1927–1958	134	20549	0.38	1.4	467	1.0
			1959–1980	110	13582	0.35	1.5	446	0.6
70410	Pechora	9620	1914–1930	302	94159	0.18	-0.4	516	−1.0
			1931–1993	276	79535	0.21	-0.3	564	−1.0
70414	Pechora	29400	1938–1956	250	65806	0.23	0.5	490	−1.0

Gauge ID	River	Catchment area [km²]	Period	m_1 [mm]	m_2 [mm²]	CV	CS/CV	$\bar{N}$ [mm]	$\bar{T}$ [°C]
			1957–1980	278	79262	0.16	0.8	601	−1.3
70466	Usa	2750	1936–1957	385	155399	0.22	1.5	483	−4.3
			1958–1980	424	185601	0.18	1.8	558	−5.3
70509	Izhma	15000	1933–1949	189	37779	0.24	0.1	465	−0.5
			1950–1980	160	26839	0.22	0.1	534	−0.9
70522	Ukhta	4290	1934–1949	170	30706	0.25	0.9	473	−0.5
			1950–1980	144	22032	0.25	0.9	535	−0.5
70531	Pizhma	4890	1937–1964	129	18041	0.29	0.9	486	−1.7
			1965–1980	150	24264	0.28	0.9	552	−2.3
71104	Kola	3780	1928–1958	182	35539	0.27	2.6	350	0.5
			1959–1994	203	43785	0.25	2.6	459	0.1
71199	Umba	6920	1931–1958	180	34762	0.27	0.6	414	−1.1
			1959–1994	149	23942	0.28	0.6	475	−1.6
71241	Yena	1600	1934–1948	100	10625	0.25	0.7	451	0.2
			1949–1980	129	18041	0.29	0.7	557	−0.3

Table 2. The model parameters and the nominally predicted multi-year statistics of the spring flood depth of runoff for the catchments selected for the cross-validation.

Notations: m_{1f} and m_{2f} are the nominally predicted first and second statistical moments of the spring flood depth of runoff; CV is the nominally predicted coefficient of variation; CS is the nominally predicted coefficient of skewness; $\bar{c}_f$ is the inverse of the runoff coefficient times the watershed reaction delay; $G_{\tilde{N}f}$ characterizes the variability of the annual precipitation amount.

Gauge ID	Lat/Lon	Period	$G_{\tilde{N}f}$ [mm²]	$\bar{c}_f$	m_{1f} [mm]	m_{2f} [mm²]	CV_f	CS_f
01176	62°06′N / 150°37′E	1934–1949	23366	3.79	115	16234	0.48	1.20
		1950–1980	24841	3.09	136	22647	0.46	1.28
01309	63°17′N / 152°02′E	1941–1956	18370	1.96	155	28815	0.44	1.38
		1957–1977	4635	1.94	141	20941	0.25	1.26
01623	62°22′N / 152°20′E	1935–1950	18208	2.88	150	25584	0.38	1.50
		1951–1980	17936	2.39	178	35398	0.34	1.54
03403	70°11′N / 113°57′E	1943–1985	6477	2.60	101	11383	0.35	0.27
		1986–2002	3799	2.26	113	13587	0.26	0.29
03414	67°24′N / 137°15′E	1935–1964	4390	4.32	42.0	2209	0.55	0.68
		1965–2002	4347	3.36	52.7	3425	0.48	0.68
03518	64°43′N / 144°37′E	1944–1985	6436	3.39	66.0	5243	0.47	0.38
		1986–2002	5167	2.61	86.9	8543	0.36	0.36
09425	65°58′N /	1941–1970	10047	2.12	233	56857	0.21	0.27

Gauge ID	Lat/Lon	Period	$G_{\tilde{N}f}$ [mm²]	$\bar{c}_f$	m_{1f} [mm]	m_{2f} [mm²]	CV_f	CS_f
	84°17′E	1971–1999	10275	1.90	258	69485	0.20	0.27
11574	64°56′N / 77°48′E	1954–1970	6625	3.39	151	23906	0.21	0.86
		1971–2001	10408	3.17	152	24718	0.27	0.27
11805	65°39′N / 72°42′E	1955–1974	8398	3.02	156	25636	0.24	0.72
		1975–1991	13505	3.36	146	23220	0.31	0.66
70047	64°41′N / 39°32′E	1928–1958	12469	2.76	200	42164	0.24	0.21
		1959–1980	14391	3.56	147	23753	0.30	0.23
70153	60°12′N / 47°00′E	1931–1946	7665	4.56	130	17612	0.22	0.46
		1947–1980	18536	4.10	140	21886	0.34	0.48
70180	61°52′N / 53°49′E	1930–1956	9022	3.34	165	28465	0.22	–0.01
		1957–1980	11481	3.29	149	23969	0.28	–0.01
70360	64°25′N / 41°03′E	1939–1958	25423	2.43	224	55552	0.32	0.38
		1959–1977	14897	3.14	170	31225	0.29	0.40
70366	64°59′N / 43°42′E	1927–1958	18073	3.49	128	18970	0.40	0.55
		1959–1980	12020	4.05	115	14749	0.33	0.51
70410	61°52′N / 56°57′E	1914–1930	10098	1.71	330	111916	0.16	–0.06
		1931–1993	13730	2.04	253	67121	0.23	–0.08
70414	62°57′N / 56°56′E	1938–1956	12960	1.96	307	97330	0.19	0.10
		1957–1980	8554	2.16	227	53351	0.20	0.15
70466	66°36′N / 60°52′E	1936–1957	18000	1.25	445	205006	0.19	0.29
		1958–1980	15331	1.32	367	140521	0.21	0.38
70509	63°49′N / 53°58′E	1933–1949	10124	2.46	217	49166	0.21	0.03
		1950–1980	8271	3.34	139	20651	0.25	0.03
70522	63°35′N / 53°51′E	1934–1949	10051	2.78	192	38779	0.22	0.19
		1950–1980	9630	3.72	127	17504	0.28	0.25
70531	65°17′N / 51°55′E	1937–1964	10545	3.77	147	22867	0.26	0.23
		1965–1980	12983	3.68	132	10205	0.32	0.30
71104	68°56′N / 30°55′E	1928–1958	9287	1.92	239	59383	0.21	0.13
		1959–1994	11647	2.26	155	26536	0.33	0.85
71199	66°52′N / 33°20′E	1931–1958	10865	2.30	207	45013	0.24	0.15
		1959–1994	11098	3.19	130	18606	0.32	0.24
71241	67°18′N / 32°08′E	1934–1948	5638	4.51	124	15878	0.20	0.53
		1949–1980	12086	4.32	104	1209	0.36	0.26

Table 3. The percentage of successful fits between the nominally predicted and empirical PDFs according to the goodness-of-fit tests for 0.05 level of statistical significance.

Version of the nominal prediction	Kolmogorov-Smirnov one-sample test	Pearson chi-squared test
No model	63	41
Model with parameterization by Kovalenko et al. (2010)	67	51
Model with regional-oriented parameterization by Shevnina (2012)	74	63

Table 4. The reference (1930–1980) and projected climatology (2010–2039) and statistics of the spring flood flow depth of runoff averaged for the entire territory of the Russian Arctic.

Multi-year statistical values	Reference climatology	Fourth Assessment Report (AR4)		Fifth Assessment Report (AR5)	
		SRES:A1B	SRES:B1	RCP 4.5	RCP 2.6
The annual amount of precipitation mean value ($\bar{N}$ mm)	378	400	402	424	424
The average annual air temperature mean value ($\bar{T}$ °C)	−10.3	−8.2	−8.2	−6.9	−7.2
The spring flood depth of runoff mean value (m_1 mm)	162	189	190	201	199
The coefficient of variation of the spring flood depth of runoff (CV)	0.30	0.30	0.29	0.29	0.25

Table 5. Projected (2010–2039) climatology and statistics of the spring flood depth of runoff averaged for the entire territory of the Russian Arctic according to the results of different climate models.

Notations: $\bar{N}$ is the mean annual precipitation amount; $\bar{T}$ is the mean annual air temperature; m_1 is the mean spring flood depth of runoff; CV is the coefficient of variation of the spring flood depth of runoff.

Dataset	Scenario	GCM	$\bar{N}$, [mm]	$\bar{T}$, [°C]	m_1, [mm]	CV
AR4	SRES:A1B	MPIM:ECHAM5	393	−8.6	184	0.30
		HadCM3	403	−7.9	191	0.30
		GFDL:CM2	404	−8.2	192	0.29
	SRES:B1	MPIM:ECHAM5	385	−8.4	182	0.30
		HadCM3	405	−8.1	191	0.30
		GFDL:CM2	415	−8.2	196	0.28
AR5	RCP4.5	MPI–ESM	421	−6.9	201	0.26
		HadGEM2–A	420	−7.0	199	0.26
		CanESM2	436	−6.7	204	0.25
	RCP2.6	MPI–ESM	415	−7.2	197	0.26

HadGEM2–A	419	−7.9	194	0.26
CanESM2	438	−6.4	207	0.24

Table 6. Climatology and the statistics of the extreme flood runoff for the Nadym River at Nadym City evaluated from the observations and under the climate projection RCP 2.6 for the period 2010–2039.

Notations: $\bar{N}$ is the mean annual precipitation amount; $\bar{T}$ is the mean annual air temperature; m_1 is the mean spring flood depth of runoff; CV is the coefficient of variation of the spring flood depth of runoff, $h_{1\%}$ is the spring flood depth of runoff with exeedance of 1%, $Q_{1\%}$ is the maximal discharge with exeedance probability of 1%.

Multi-year values	Period of 1954–1980	Result according to GCM			
		HadGEM2-A	MPI-ESM-LR	CanESM2	Multi model
$\bar{N}$ mm	431	483	491	519	498
$\bar{T}$ °C	−5.9	−4.0	−2.9	−2.4	−3.1
m_1 mm	160	180	184	197	187
CV	0.28	0.25	0.23	0.19	0.22
$h_{1\%}$ mm	277	297	293	297	296
$Q_{1\%}$ m^{3}s^{-1}	8572	9177	9062	9191	9144
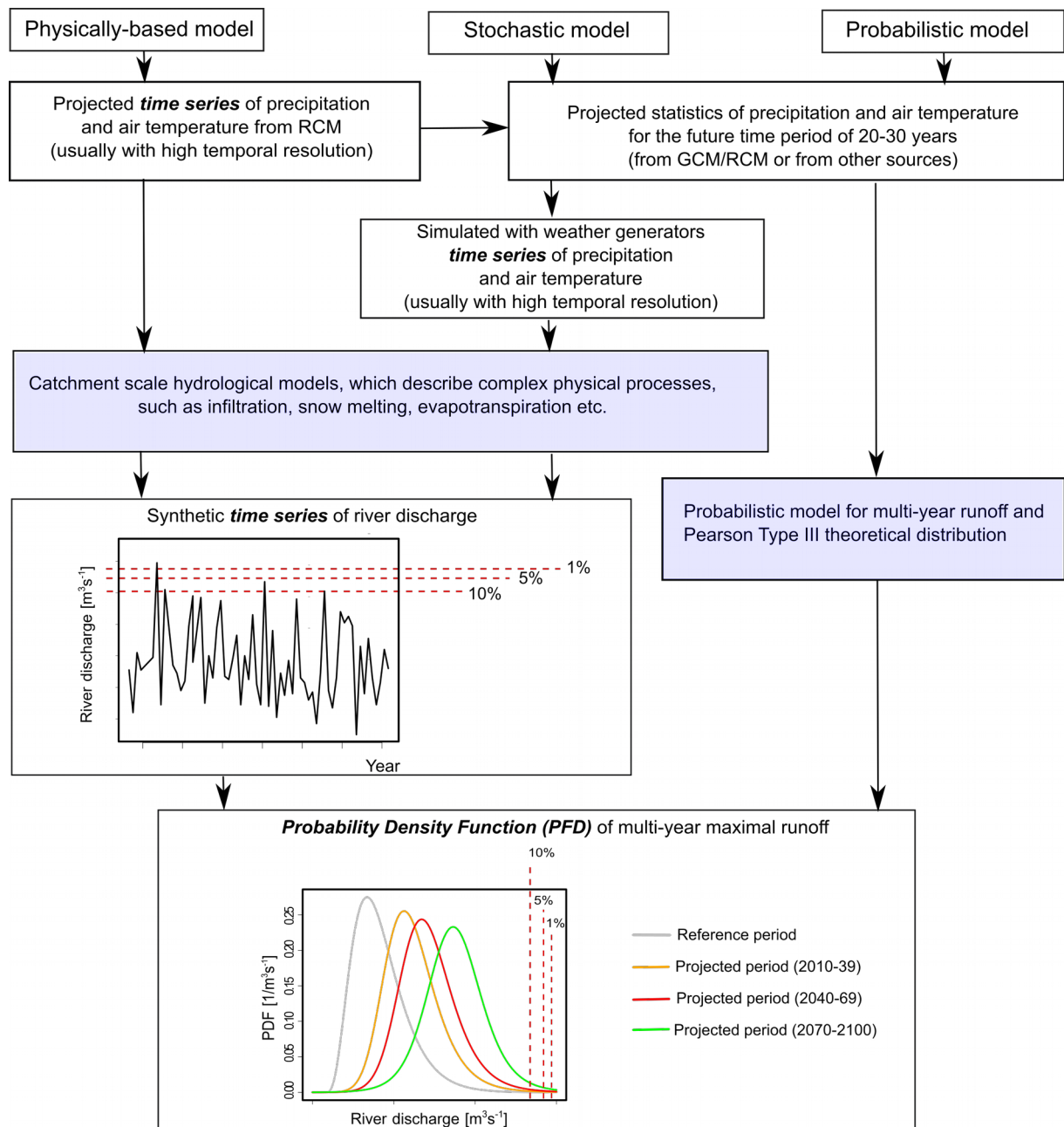
Figure 1. Three approaches to evaluate a hydrological response to the expected climate change.
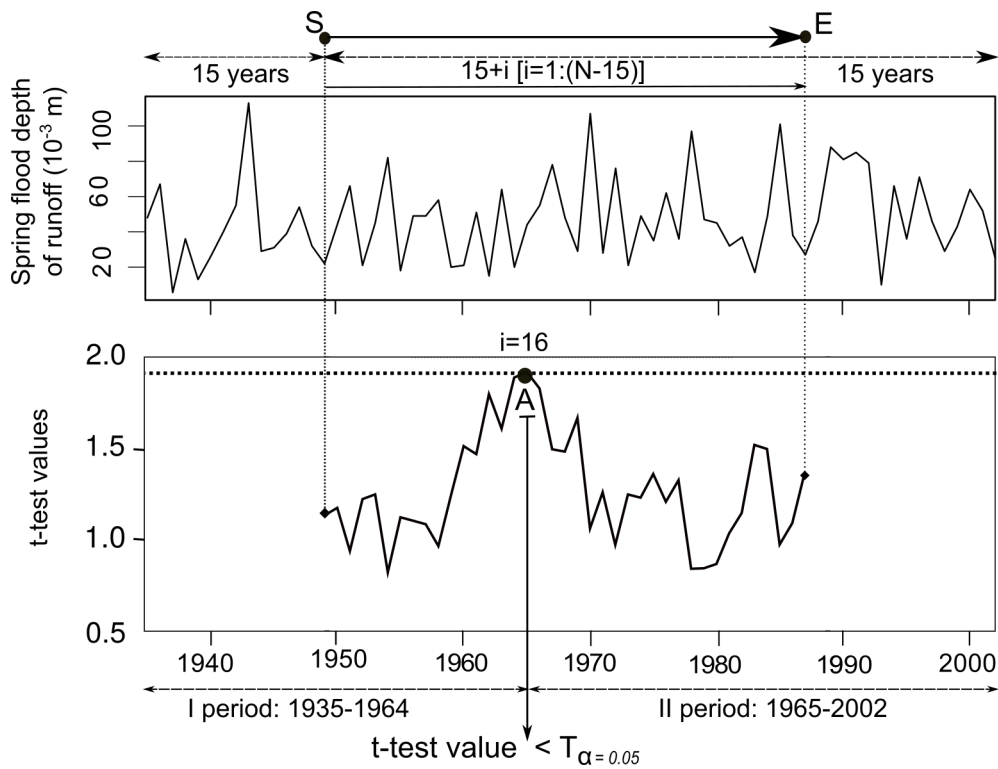
Figure 2. The partition of the observed time series of the spring flood depth of runoff (top) into sub-periods with statistically significant shift in the mean value by *t*-test (bottom) for the Yana River at Verkhoyansk City gauge: $T_{\alpha=0.05}$ is the critical value of the *t*-test at the threshold of the statistical significance equal to 0.05 (dotted line on bottom). See the text for the explanation of A, S, E, N and i.
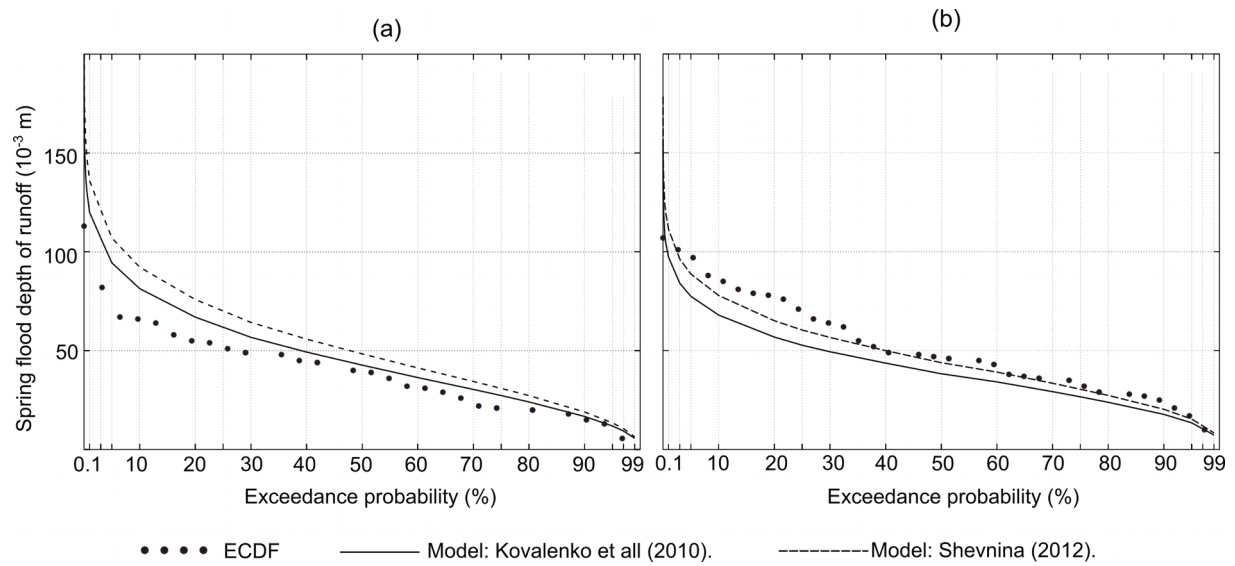
Figure 3. The nominally predicted exceedance probability curves compared with the empirical exceedance probability (ECDF) for the sub-periods with statistically significant shift in the mean value for the Yana River at Verkhoyansk City: (a) – the period of 1935–1964; (b) – the period of 1965–2002.
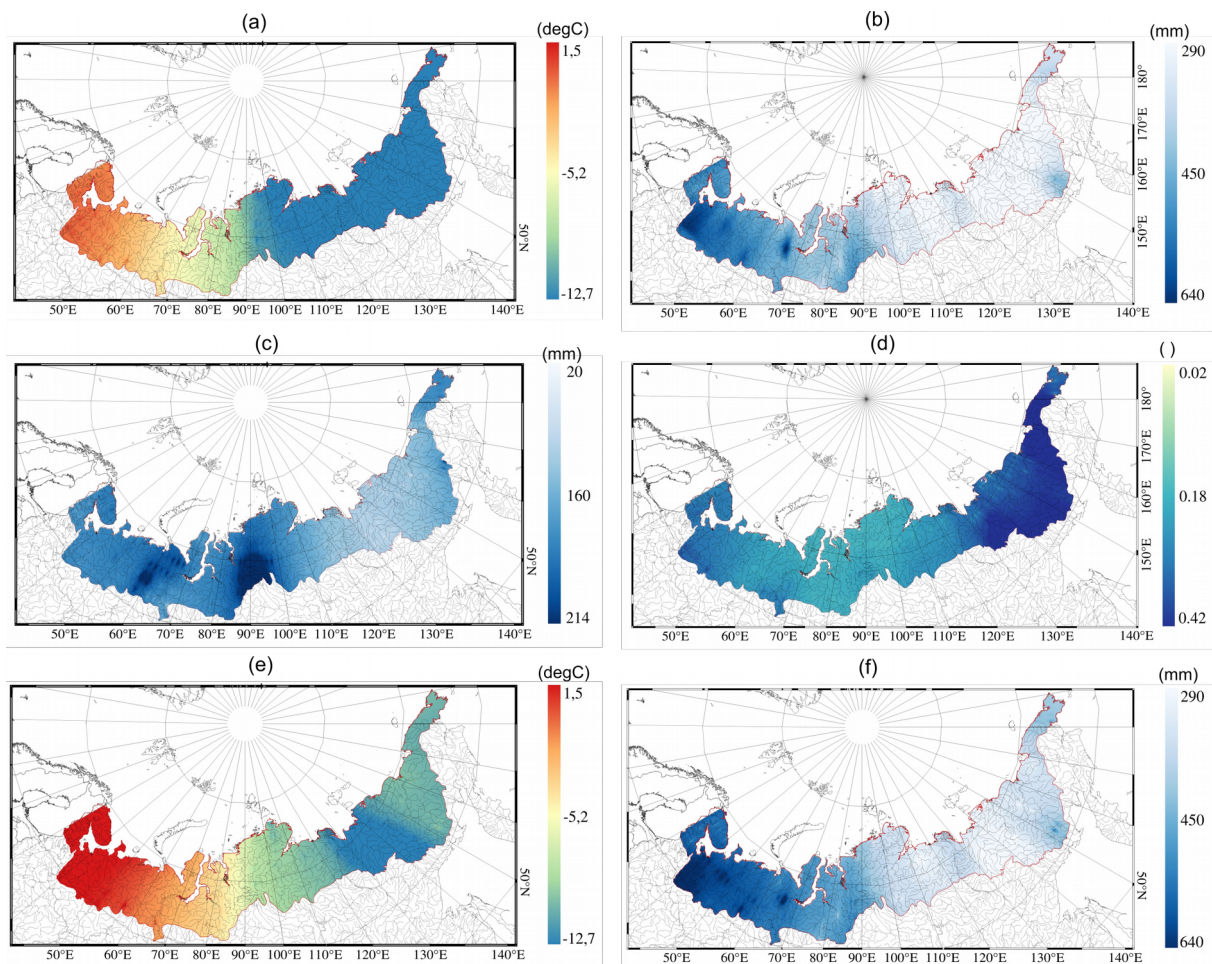
Figure 4. The data used in the study: (a) – the mean values of the annual air temperature for the reference period (Radionov and Fetterer, 2003; Catalogue, 1989); (b) – the mean values of the annual precipitation amount for the reference period (Radionov and Fetterer, 2003; Catalogue, 1989); (c) – the mean values of the spring flood flow depth of runoff for the reference period (Vodogretskiy, 1986); (d) – the coefficients of variation of the spring flood flow depth of runoff for the reference period (Rogdestvenskiy, 1986); (e) – the mean values of the annual air temperature for the projected period (2010– 2039) under the RCP 4.5, average of four GCMs (Taylor et al., 2012); (f) – the mean values of the annual precipitation amount for the projected period (2010– 2039) under the RCP 4.5, average of four GCMs (Taylor et al., 2012). The territory of the Russian Arctic is outlined according to Ivanov and Yankina (1991).
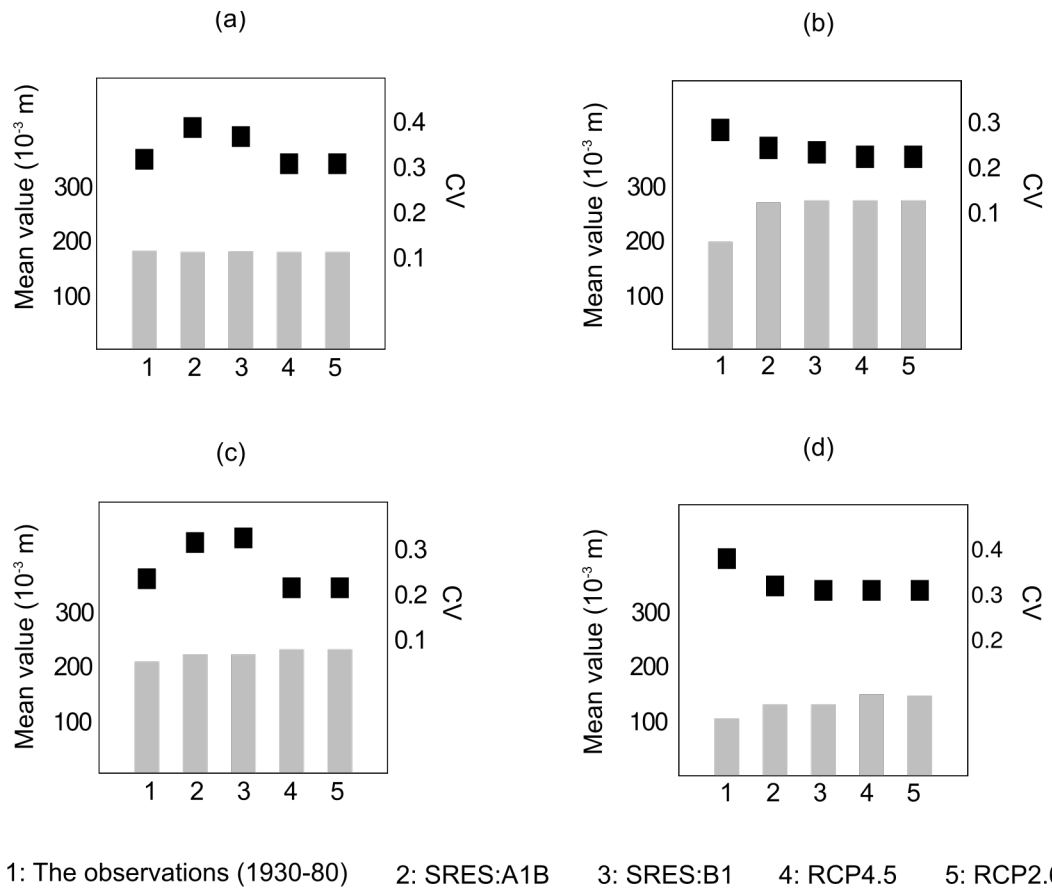
Figure 5. The observed and projected the mean values (bars) and coefficients of variation (squares) of the spring flood depth of runoff expected for the regions of the Russian Arctic for the period 2010–2039: (a) – the Kola Peninsula and Karelia, (b) – Arkhangelsk Oblast and the Komi Republic; (c) – West Siberia; (d) – East Siberia.
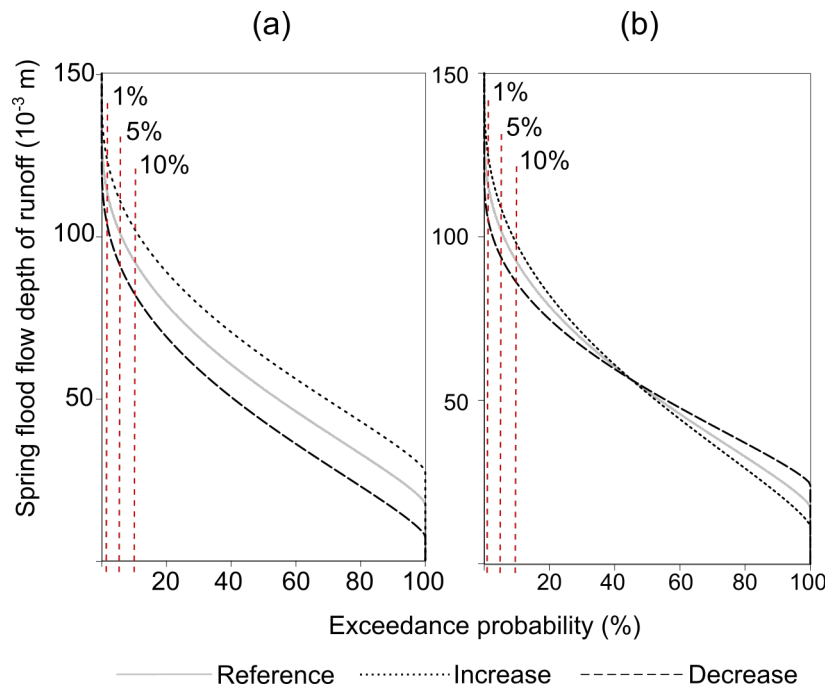
Figure 6. Schematic explanation of the changes in the upper-tail values due to changes in the parameters of the exceedance probability curve: (a) – the mean value and (b) – the coefficient of variation.
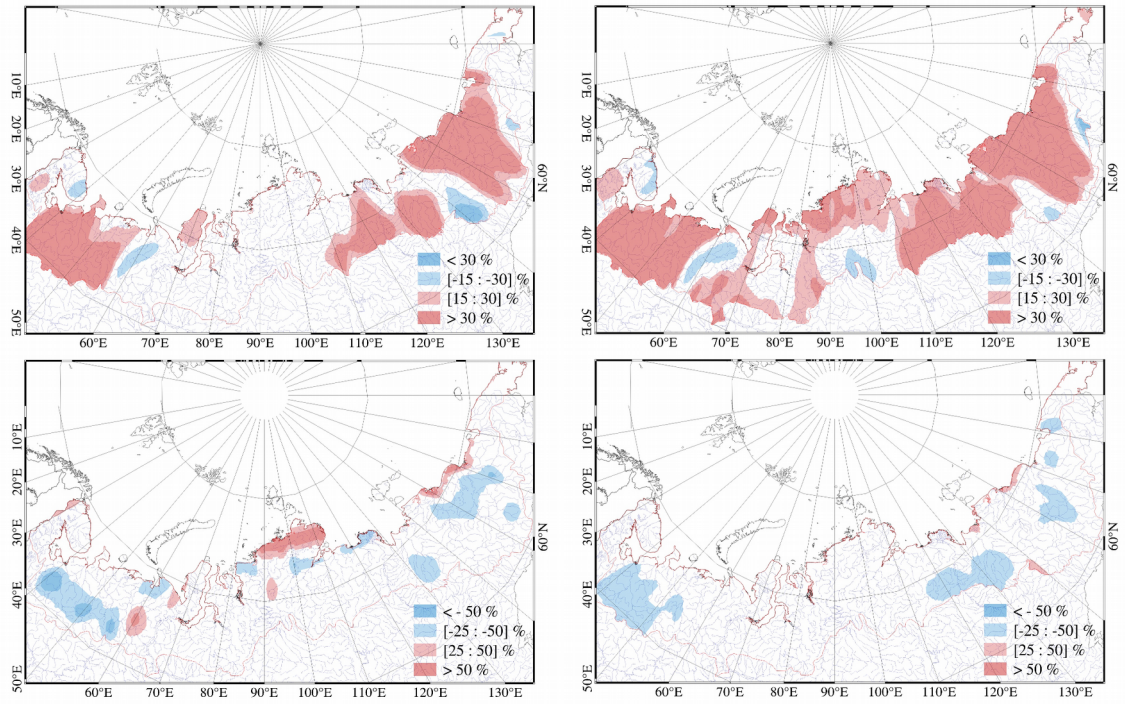
Figure 7. The regions with substantial changes in the mean values (top) and coefficients of variation (bottom) of the spring flood depth of runoff according to the MPIM:ECHAM5 under the SRES:B1 (left) scenario and the MPI-ESM-LR under the RCP 2.6 scenario (right).
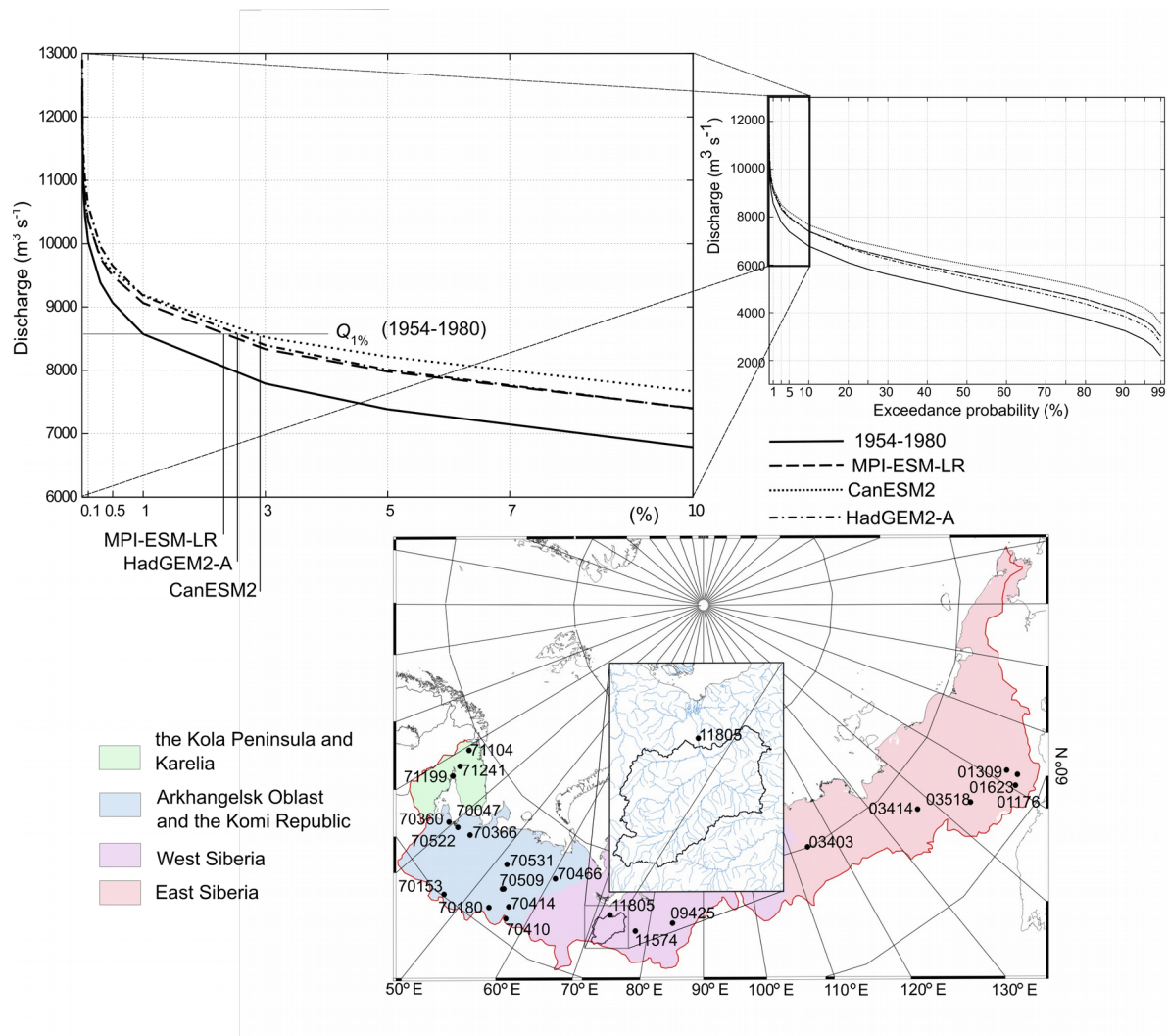
Figure 8. Top: the exceedance probability curves of the peak-flow discharge for the period 1954–1980 and for the projected period 2010–2039 under the RCP 2.6 scenario for the Nadym River at Nadym City (11805). Bottom: the considered regions of the Russian Arctic, the watershed of the Nadym River and location of the gauges used for the model cross-validation.